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FLUID FLOW IN WOOD: INVESTIGATION OF THE INFLUENCE OF LASER INCISION PARAMETERS ON UPTAKE AND FLOW PATHS IN FOUR WOOD SPECIES

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ABSTRACT

Laser incision offers great potential for increasing the permeability of wood to preservative or other fluids. Wood modification systems have a greater requirement for full impregnation than traditional preservative systems, and envelope treatments are not sufficient. The bulking effect of many wood modification systems means that uniformity of penetration by reagents is essential. Therefore laser incision offers potential to increase permeability of timber for wood modification. Experiments were conducted on four species of wood, to investigate the altered flow. These species were southern yellow pine, European beech, Sitka spruce and European redwood.

Blocks were sealed on all faces, limiting fluid uptake to a single laser incision. Laser incisions were made using UV laser, and the depth of focus and number of shots was varied. Pressure treatment was undertaken using an aqueous dye system, and quantities of fluid taken up were recorded gravimetrically, as well as by observation of the dye within dissected wood blocks. This allowed observation and measurement of longitudinal and transverse flow within different planes in the sample.

The significance of the resin canal network was demonstrated in some species (southern yellow pine) while pit aspiration dominated the reduced flow observed for spruce. Hardwood flow is dominated by the vessel network. As a result of these flow observations different incision strategies will be developed to maximise fluid uptake and distribution uniformity in species selected for further study.

INTRODUCTION

Many wood modification industries are seeking to expand the range of timber species which can be used in modification systems. Chemical and resin treatment systems require reagents to be transported deep into the timber, to ensure uniform treatment throughout the cross section. As a result of limited availability of high permeability species such as radiata pine sapwood it has become necessary to reconsider species of moderate permeability for their suitability. Laser incision offers great potential in increasing the permeability of wood. A number of incision systems have been used in the preservative treatment industry over the years (Morris *et al.* 1994), however it is only those with relatively small incision diameter which have been considered for wood modification.

The potential for laser systems to precisely control incision size and depth, and to reduce any damage to surrounding tissue, has been noted. However, in adapting laser incision technology for wood modification several additional considerations arise which are less significant in the traditional pressure treatment of wood with preservatives, where an envelope treatment would be permissible. Resin modification relies in part on a bulking effect, with timber increasing in volume during treatment, and retaining a larger size after drying and curing (Hill 2007, Stefanowski *et al*. 2018). If penetration by the treatment system is incomplete, then distortion may occur, or stresses may develop within the piece, potentially generating cracks and checks on drying.

To assess the permeability of several candidate timber species, a set of preliminary experiments were conducted on small timber samples with laser incisions at a single location. Impregnation using a pigmented system allowed observation of the flow patterns within the wood originating from this incision. These studies have highlighted significant differences in the flow paths between wood species, and alterations in the magnitude of flow in each of the principle directions within the wood (tangential, radial and longitudinal). These species were southern yellow pine (*Pinus* spp. including *P. palustris, P. elliotti, P. echinata, P. taeda*), European beech (*Fagus sylvatica*), Sitka spruce (*Picea sitchensis*) and European redwood (*Pinus sylvestris*).

MATERIALS AND METHODS

Blocks of 20 x 20 x 100mm (R x T x L) were prepared from southern yellow pine, beech, spruce and European redwood. The blocks were sealed on all faces using a transparent floor lacquer, limiting fluid uptake to the laser incision only. Laser incisions were made into one long face of each block using UV laser, and the depth of focus and number of shots was varied. Incisions were made into both the radial and the tangential faces, on different blocks of the same species. In some species additional samples were selected with half radial or half tangential grain alignment. The laser used was a frequency tripled pulsed Nd:YAG laser, working at wavelength 355nm. Further details regarding laser methodology will be reported in Nath *et al.* (2018).

A pressure treatment was conducted using an aqueous blue dye in a small pressure treatment vessel. This pressure cycle was selected to mimic commercial empty cell processes, using a vacuum period prior to impregnation under pressure (12 bar) for one hour, followed by a vacuum to drain any surplus fluid from the samples. Quantities of fluid taken up were recorded gravimetrically. Blocks were then cross cut to observe the distribution of the dye internally. Different planes of dissection were used to investigate the longitudinal and transverse flow.

RESULTS

Treated samples were weighed before and after impregnation, allowing evaluation of the fluid uptake through the single incision. Uptake in southern yellow pine (SYP) was significantly higher than in all other species (Table 1). The uptake in Sitka spruce was the lowest of the species tested.

Table 1: Observed uptake of fluid in the sealed samples with a single laser incision.

	% weight taken up	Distance longitudinally	Distance laterally
Redwood	7.92	30.4mm	0.5 to 4mm
Spruce	3.05	4.25mm	0.5mm
Beech	15.6	Greater than 50mm	0.5mm
Southern yellow pine	102.2	30mm in latewood, 47mm in resin canals	9mm radially 0.5mm tangentially

In addition, distances travelled by the blue dye were recorded by visual observation. This was visually observed in both the longitudinal and lateral directions (ruler accuracy), to assist in defining a typical ellipse of treatment, as discussed in Morris et al. (1994) for incised woods. Figure 1 shows that while an approximately elliptical pattern was visible, this was strongly influenced by differences between earlywood and latewood longitudinal permeability.

Figure 1. Samples of (a) European redwood and (b) Southern yellow pine, incised with UV laser (355nm) prior to dissection, showing extended longitudinal flow.

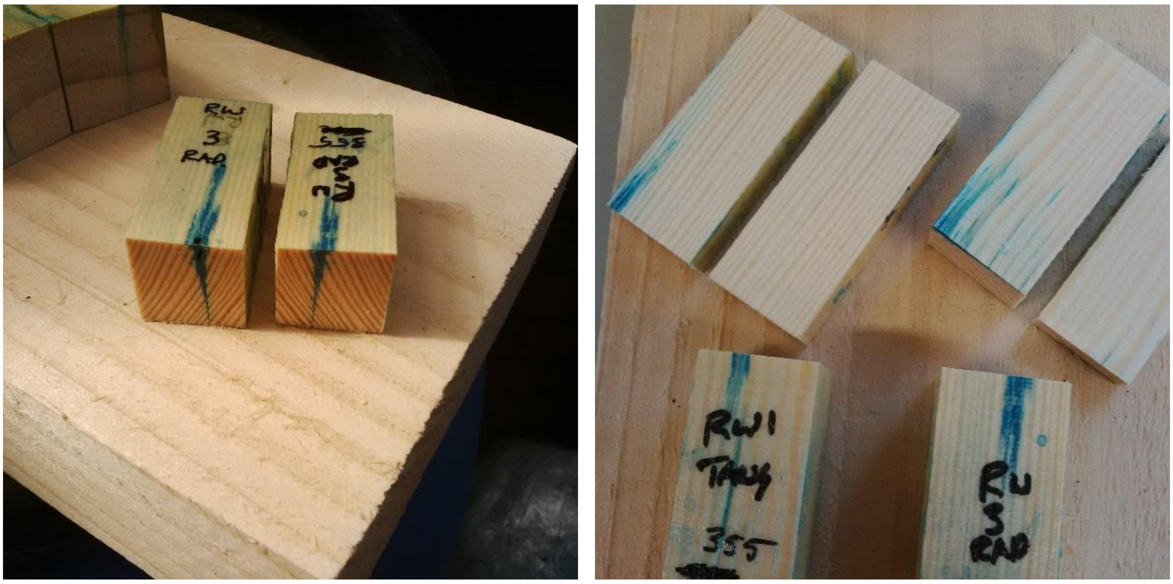

Figure 2. (a) Longitudinal flow is preferential in the latewood of redwood heartwood, with only minor radial flow away from the incision line (incised in the half radial face). (b) Longitudinal flow is preferentially located in latewood of redwood samples, whether incised into tangential (left) or radial (right) face. There was also evidence of longer distance flow within the resin canal system.

When the samples were cross cut approx. 1mm below the incision, the profile of fluid extending outwards from the incision was observed. In Figure 2 a sample with half radial orientation reveals a tendency for the fluid to migrate along the latewood of the growth ring. This has extended the zone of treatment by up to 2.5mm laterally. However earlywood penetration was lower. Figure 2b also indicates that this trend extends longitudinally, with fluid accessing latewood for several centimetres from the incision. Isolated blue flecks at a greater distance from the incision relate to fluid flow in the resin canal network.

Southern yellow pine revealed a very strong radial influence (Figure 3b-d), in addition to the influence of resin canals.

Figure 3. (a) Cross section of southern yellow pine, made just below the laser incision to reveal longitudinal flow from the incision. (b) For a radial incision in SYP, the cascade pattern of impregnation in earlywood and latewood, revealing radial transport of fluid in addition to longitudinal flow. (c) Prominent radial transport of fluid away from laser incision region in a tangentially incised sample of SYP. (d) Radial flow of fluid away from incision line in an incision into a half-radial face of SYP.

Sitka spruce showed the lowest degree of permeability of the species tested. The incision permitted fluid to penetrate into the wood to the depth of the incision, but longitudinal flow outwards from this incision was minimal (Figure 4b).

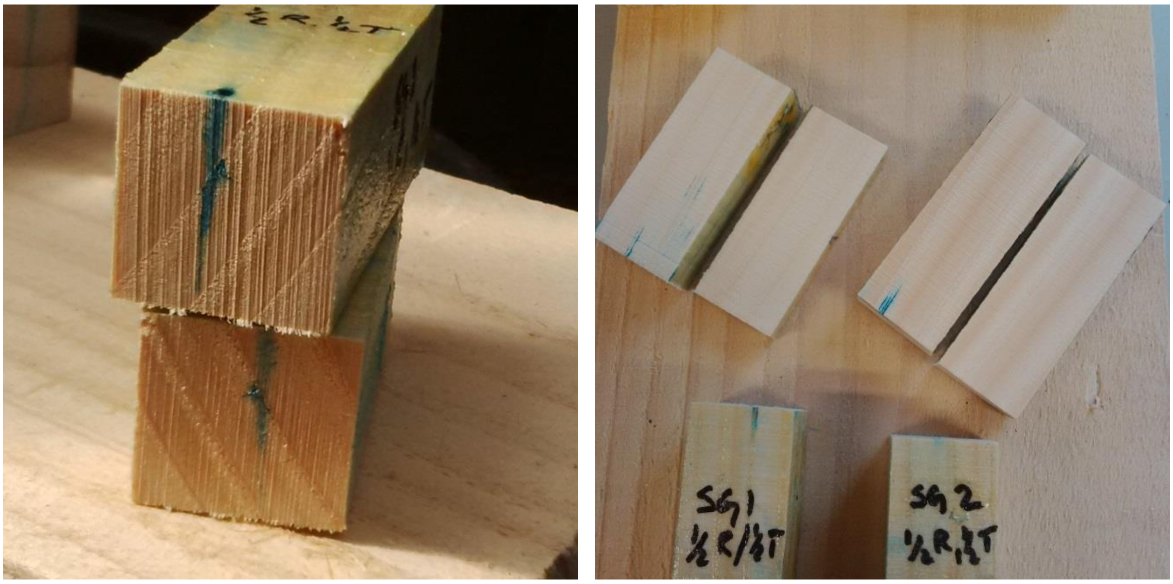

Figure 4. (a) Sitka spruce, incised in the half radial face, revealing small deflection of fluid flow into the latewood-earlywood boundary, but minimal evidence of radial flow. (b) Sitka spruce revealed preferential fluid flow in the resin canals, when cross cut parallel to the grain adjacent to the laser incision

Samples of incised beech showed a very different treatment pattern than the softwoods. In this hardwood species, the permeability longitudinally was excellent (Figure 5), but limited to the vessel network. When observed under the microscope, the location of the dye was limited to vessel elements and only immediately adjacent cells (Figure 6). As a result, although the fluid travelled a long distance, the treatment would be limited to only a fraction of the tissue present.

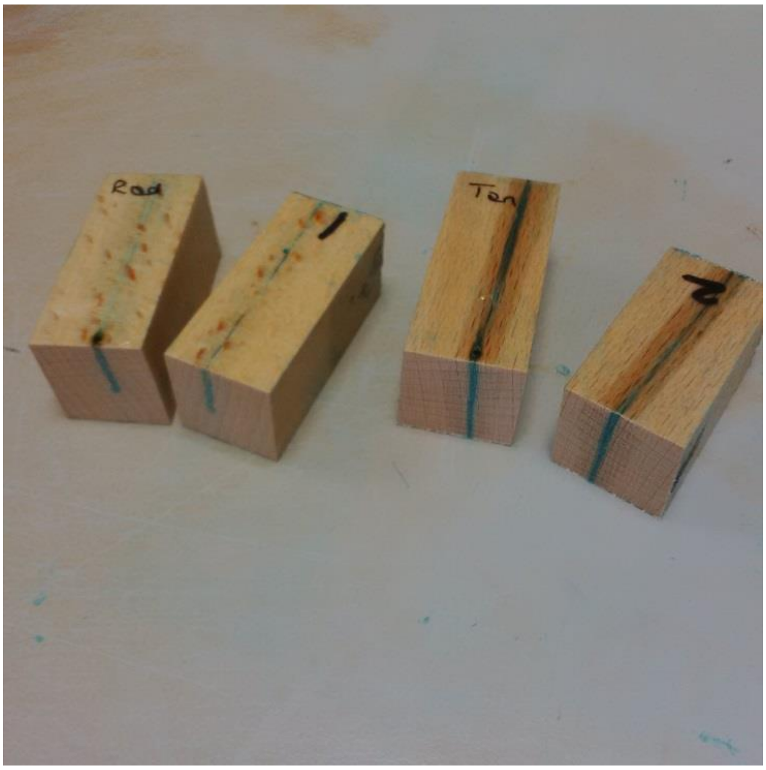

Figure 5. Samples of beech incised into the radial face (left) and tangential face (right), revealing longitudinal flow through the full length of the sample, but minimal lateral flow.

An unexpected observation was the negligible treatment of the ray tissue in beech. In all samples it was clear both visually and by microscopy, that the ray tissue had not received any of the blue pigment.

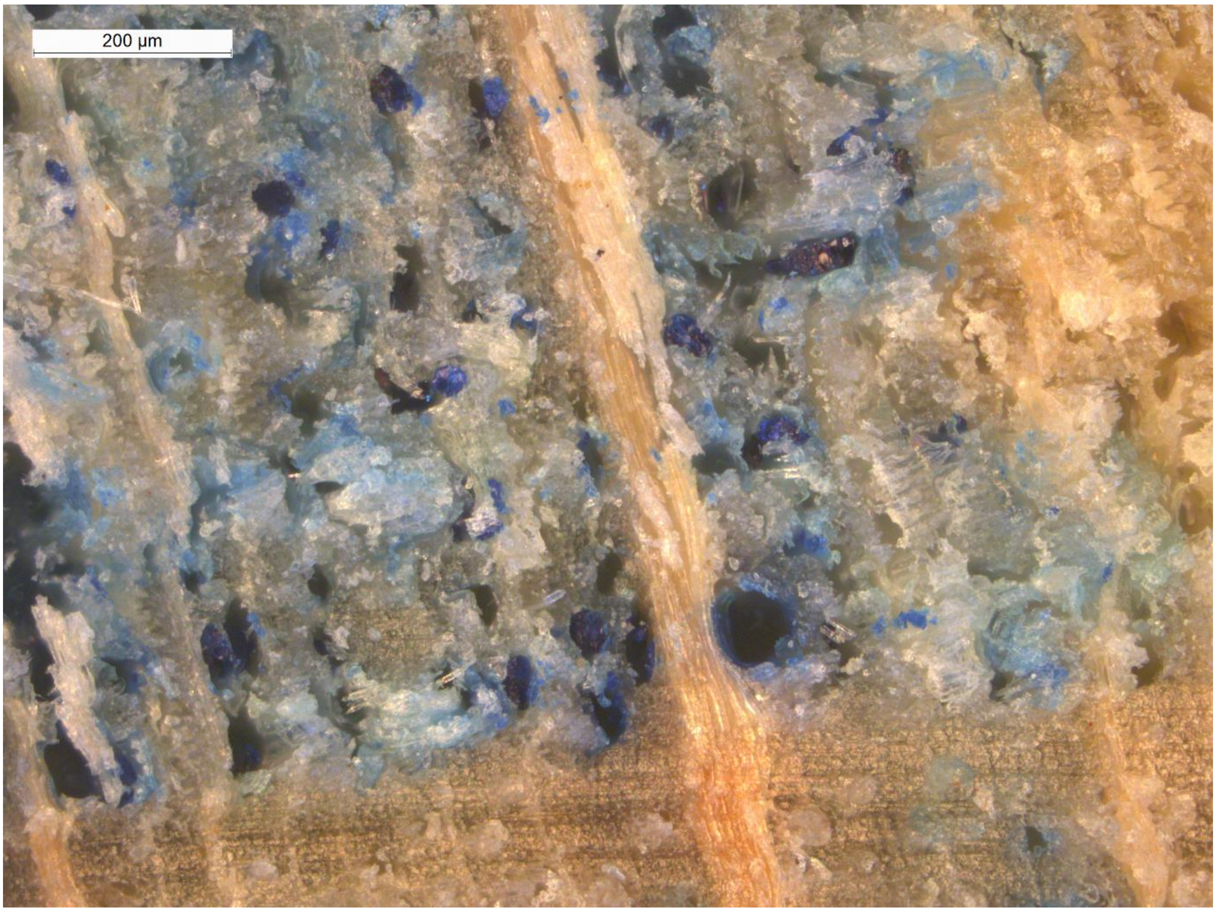

Figure 6. Micrograph of transverse section of beech, revealing limited access of fluid into rays, but strong association of blue pigment with vessel tissue.

DISCUSSION

It is well known that the cellular structure of wood influences permeability, with an additional hindrance effect due to bordered pits in the tracheids of softwoods (Petty 1972, Eaton and Hale 1993). The preferential flow in the latewood rather than earlywood of many softwoods relates to the lower degree of pit aspiration in latewood tracheids due to relative inflexibility of the pit membrane, and the interaction of the geometry of the bordered pit with the meniscus of the retreating fluid. However, the diameter of latewood tracheids is smaller than that of earlywood, so flow in timber once dried is considerably slower than in the living tree. The preferential flow of fluid in the latewood was demonstrated in the pine and spruce species treated in this study, as expected.

Traditionally the good impregnation of pine sapwood has been attributed to the wide crossfield pits between tracheids and rays (Banks 1970, Eaton and Hale 1993). This enables flow between tracheids and ray parenchyma, allowing fluid to access an increased area of tissue. This radial flow was seen in several samples, and was prominent in the Southern yellow pine.

Some transverse flow from tracheid to tracheid through the latewood has also been proposed, due to the location of bordered pits in the radial walls of the tracheids, many of them concentrated at the cell ends (Usta and Hale 2006). The overlapping cell ends of the tracheids primarily provide connected longitudinal flow from one cell to the next, but also permit a small amount of transverse flow.

However, two additional effects were observed in the pine species. Firstly, in the southern yellow pine and the redwood, the resin canals appeared to play a significant role in transporting fluid over relatively long distances, both longitudinally and radially. Once in the resin canal system however, flow of fluid outwards into neighbouring tracheids was poor. Secondly, where laser incision allowed fluid to enter the wood and longitudinal flow occurred through latewood tracheids, there was a saturation and cascade effect between growth rings. Notably the latewood became well impregnated, until one or more routes through the rays into the neighbouring earlywood tissue were opened up. Flow through earlywood appeared to be through relatively few channels, but a further pooling of fluid in the latewood of the next growth ring occurred, prior to flow through the rays into the next growth ring.

Banks (1970) proposed that in refractory species such as spruce, the flow in longitudinal and tangential directions was typically six cells deep. Thus for longitudinal tracheids of approx. 2.5mm length, the flow decreases to a minimum at approx. 1.5cm depth; whereas tangentially with a cell diameter of approx. 50 microns, the flow diminishes to a minimum over approx. 0.03cm, making sample preparation and measurements in this orientation more problematic. In the radial direction, where a different set of anatomical features contribute to flow, the minimum is seen at approximately 0.5cm. These general principles were demonstrated in the laser incised spruce samples, with very limited axial permeability, and near zero lateral penetration of the wood adjacent to the laser incision. As a result, laser incision of spruce appears unlikely to provide a sufficient level of penetration to permit wood modification processes.

The good permeability of beech, relative to other hardwoods is widely recognised, for example Eaton and Hale (1993) report longitudinal permeability of 23.53 darcys, compared to 2.53 darcys for elm and 0.20 darcys for European ash. Beech is the routinely used hardwood species in preservative treatment tests, such as EN 113 due to good longitudinal permeability. The relatively poor impregnation of ray tissue in beech was unexpected, however relatively few studies have previously used beech with sealed end grain to evaluate permeability to liquids in the radial and tangential orientations.

CONCLUSIONS

This screening exercise has indicated that several pine species show potential for laser incision, with moderate to good longitudinal flow outwards from the incisions. Pit aspiration dominated the very low flow observed for spruce. Laser incisions in spruce would require to be very close spaced to achieve full impregnation with treatment agent.

Rays were seen to play a role in fluid flow in southern yellow pine, but to totally resist flow in beech. The significance of the resin canal network was also demonstrated in the pine species, permitting long range flow of fluids, however migration outwards from the resin canal system was poor.

Flow in beech was dominated by the vessel network, especially within the earlywood where vessels are of large diameter. As a result of these flow observations different incision strategies will be developed to maximise fluid uptake and distribution uniformity in species selected for further study.

ACKNOWLEDGEMENTS

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